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CP-violating asymmetries in $e^+e^- \to t\bar{t}$ with longitudinally polarized electrons

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Abstract

New CP-violating asymmetries of decay leptons in $e^+\,e^- \;\to\; t\,\bar{t}$, arising from electric and weak dipole couplings of $t\,\bar{t}$ to γ and Z, are examined in the case of unpolarized and longitudinally polarized electrons. The new asymmetries measured together with the old ones can help to determine independently the real and imaginary parts of the electric as well as weak dipole couplings. Longitudinal beam polarization, if present, obviates the need for the simultaneous measurement of more than one asymmetry, and enhances considerably the sensitivity to the CP-violating parameters. Numerical results are presented for the Next Linear Collider with $\sqrt{s} = 500$ GeV and $\int \mathcal{L}\,dt \;=\; 10\,\mathrm{fb}^{-1}$.

Experimental results at the $p\bar{p}$ collider Tevatron at Fermilab [1] indicate that the top quark is heavy ($m_t = 174 \pm 10^{+13}_{-12}$ GeV), as anticipated from the LEP results and one-loop radiative corrections in the standard model (SM). It has been suggested that a heavy top ($m_t > 120$ GeV) would decay before it can hadronize [2], and therefore its decay products would preserve useful information on its polarization. This information could be utilized, for example, in investigating possible CP violation in $t\,\bar{t}$ production in hadronic and $e^+\,e^-$ collisions [3-7].

At the present time, CP violation has only been seen in the K-meson system. While these observations are consistent with CP violation arising from a single phase in the Cabibbo-Kobayashi-Maskawa matrix in SM, there are several extensions of SM which can accommodate the observed CP violation. Some of these models predict enhanced CP violation for a heavy top quark [4,5], which could show up in a CP-violating electric-dipole type $t\,\bar{t}\,\gamma$ vertex and an analogous "weak"-dipole $t\,\bar{t}\,Z$ vertex. An observation of these would be interesting and useful from the theoretical point of view.

Proposals have been recently forwarded on using top polarization asymmetry, and subsequent asymmetry in the decay distributions [3,5,6], to measure CP violation in top production[1]. The measurement of CP-odd correlations among the momenta of the decay products can also be used for the purpose [4,7]. In principle, the effective dipole couplings can be complex. Thus, measurements of CP asymmetries which are T-odd (like the decay lepton energy asymmetry) give information on the real parts of the dipole couplings, whereas those which are T-even (like the decay-lepton up-down asymmetry about the production plane) can measure the imaginary parts. However, at high-energies required for top production, when both γ and Z propagators are comparable, one still has to try and disentangle the electric (c_d^γ) and weak dipole (c_d^Z) couplings from each other. This problem has not received much attention, and is one of the issues we discuss here. We suggest that this needs either studying additional asymmetry parameters, or better still, using polarized beams[2].

The purpose of this note is two-fold: firstly, we extend the analysis of

[1] CP violation in top decays has also been considered. See, for example, Ref. [8].

[2] The advantage of using polarized beams in the context of momentum correlations of $t, \bar{t}$ decay products was pointed out in [7].

Chang *et al.* [5] to study new asymmetries in $e^+e^- \to t\bar{t}$ which are useful to get information on c_d^γ and c_d^Z separately. Secondly, we propose the use of longitudinal electron polarization, which would be available at linear colliders, to help in disentangling c_d^γ from c_d^Z. The sensitivity in that case is considerably improved, as we shall see.

The process we consider is

$$e^+(p_e) \; + \; e^-(p_{\bar{e}}) \; \to \; t(p_t) \; + \; \bar{t}(p_{\bar{t}}), \tag{1}$$

with subsequent decay of either t or $\bar{t}$ via the leptonic channel,

$$\begin{aligned} t\,(p_t) \quad &\to \quad b \; + \; l^+\,(p_{l^+}) \; + \; \nu_l, \\ \bar{t}\,(p_{\bar{t}}) \quad &\to \quad \bar{b} \; + \; l^-\,(p_{l^-}) \; + \; \bar{\nu}_l. \end{aligned} \tag{2}$$

We have in mind a future $e^+\,e^-$ collider, the Next Linear Collider (NLC), and for definiteness we will assume the centre of mass (cm) energy to be 500 GeV.

We assume the top quark to have couplings to γ and Z to be given by the vertex factor $ie\Gamma_\mu^j$, where

$$\Gamma_\mu^j \; = \; c_v^j\,\gamma_\mu \; + \; c_a^j\,\gamma_\mu\,\gamma_5 \; + \; \frac{c_d^j}{2\,m_t}\,i\gamma_5\,(p_t \; - \; p_{\bar{t}})_\mu, \;\; j \; = \; \gamma, Z, \tag{3}$$

with

$$\begin{aligned} c_v^\gamma \;\; &= \;\; \frac{2}{3}, \;\; c_a^\gamma \; = \; 0, \\ c_d^Z \;\; &= \;\; \frac{\left(\frac{1}{4} - \frac{2}{3}\,x_w\right)}{\sqrt{x_w\,(1-x_w)}}, \\ c_a^Z \;\; &= \;\; -\frac{1}{4\sqrt{x_w\,(1-x_w)}}, \end{aligned} \tag{4}$$

and $x_w = sin^2\theta_w$, θ_w being the weak mixing angle [3]. We have assumed in (3) that the only addition to the SM couplings $c_{v,a}^{\gamma,Z}$ are the CP-violating electric and weak dipole form factors, ec_d^γ/m_t and ec_d^Z/m_t, which are assumed small.

[3]We largely adopt the notation of Chang *et al.* [5], to facilitate comparison.

Use has also been made of the Dirac equation in rewriting the usual dipole coupling $\sigma_{\mu\,\nu}\,(p_t - p_{\bar{t}})^\nu\,\gamma_5$ as $i\,\gamma_5\,(p_t - p_{\bar{t}})_\mu$, dropping small corrections to the vector and axial-vector couplings. We assume that there is no CP violation in t, $\bar{t}$ decay.

Using (3) to leading order in the dipole couplings, we have calculated the following leptonic asymmetries for arbitrary longitudinal electron (positron) beam polarizations P_e $(P_{\bar{e}})$[4]:

1. The energy asymmetry [5]

$$A_E(x) \;=\; \frac{1}{\sigma}\left[\frac{d\sigma}{dx\,(l^+)} \;-\; \frac{d\sigma}{dx\,(l^-)}\right], \tag{5}$$

between distributions of l^+ and l^- at the same value of $x = x(l^+) = x(l^-) = 4\,E(l^\pm)/\sqrt{s}$.

2. The up-down asymmetry [5] $A_{ud} \;=\; \int_{-1}^{+1} A_{ud}(\theta)\,d\cos\theta$, where

$$A_{ud}(\theta) = \frac{1}{2\,\sigma}\left[\frac{d\,\sigma(l^+,\mathrm{up})}{d\,\cos\theta} - \frac{d\,\sigma(l^+,\mathrm{down})}{d\,\cos\theta} + \frac{d\,\sigma(l^-,\mathrm{up})}{d\,\cos\theta} - \frac{d\,\sigma(l^-,\mathrm{down})}{d\,\cos\theta}\right], \tag{6}$$

Here up/down refers to $(p_{l^\pm})_y \gtrless 0$, $(p_{l^\pm})_y$ being the y component of $\vec{p}_{l^\pm}$ with respect to a coordinate system chosen in the $e^+\,e^-$ center-of-mass (cm) frame so that the z-axis is along $\vec{p}_t$, and the y-axis is along $\vec{p}_e \times \vec{p}_t$. The $t\bar{t}$ production plane is thus the xz plane. θ refers to the angle between $\vec{p}_t$ and $\vec{p}_e$ in the cm frame.

3. The combined up-down and forward-backward asymmetry:

$$A_{ud}^{fb} \;=\; \int_0^1 A_{ud}(\theta)\,d\cos\theta \;-\; \int_{-1}^0 A_{ud}(\theta)\,d\cos\theta, \tag{7}$$

with $A_{ud}(\theta)$ given in (6).

4. The left-right asymmetry $A_{lr} \;=\; \int_{-1}^{+1} A_{lr}(\theta)\,d\cos\theta$, where

$$A_{lr}(\theta) = \frac{1}{2\,\sigma}\left[\frac{d\,\sigma(l^+,\mathrm{left})}{d\,\cos\theta} - \frac{d\,\sigma(l^+,\mathrm{right})}{d\,\cos\theta} + \frac{d\,\sigma(l^-,\mathrm{left})}{d\,\cos\theta} - \frac{d\,\sigma(l^-,\mathrm{right})}{d\,\cos\theta}\right], \tag{8}$$

[4]We have restricted ourselves to asymmetries for which analytic expressions could be obtained.

Here left/right refers to $(p_{l^\pm})_x \gtrless 0$.

5. The combined left-right and forward-backward asymmetry

$$A_{lr}^{fb} \;=\; \int_0^1 A_{lr}(\theta)\, d\cos\theta \;-\; \int_{-1}^0 A_{lr}(\theta)\, d\cos\theta, \tag{9}$$

with $A_{lr}(\theta)$ given in (8).

All these asymmetries are a measure of CP violation in the unpolarized case and in the case when polarization is present, but $P_e = -P_{\bar{e}}$. When $P_e \neq -P_{\bar{e}}$, the initial state is not invariant under CP, and therefore CP-invariant interactions can contribute to the asymmetries. However, to the leading order in α, these CP-violating contributions vanish in the limit $m_e = 0$. Order-α collinear helicity-flip photon emission can give a CP-invariant contribution to the T-even asymmetries (A_E, A_{lr}, A_{lr}^{fb}). However, this background can be suppressed by a suitable cut on the visible energy. The T-odd asymmetries A_{ud} and A_{ud}^{fb} are genuine measures of CP violation even to order α, since an absorptive part, required for a CP-even and T-odd amplitude, is not possible to that order.

Of these asymmetries, the energy asymmetry and up-down asymmetry were discussed by Chang *et al.* [5]. The remaining are new, and as we shall see, they help to measure different combinations of $\mathrm{Re}\, c_d^\gamma$ and $\mathrm{Re}\, c_d^Z$ or $\mathrm{Im}\, c_d^\gamma$ and $\mathrm{Im}\, c_d^Z$, thus making possible a complete determination of all the parameters. A_E alone can only give one of $\mathrm{Im}\, c_d^\gamma$ or $\mathrm{Im}\, c_d^Z$, assuming the other to be zero (or known). A similar statement is true of A_{ud} and $\mathrm{Re}\, c_d^{\gamma,Z}$.

We give below expressions for the asymmetries in terms of c_d^i[5]:

$$\begin{aligned}
A_E(x) \;=\;& \frac{2\,\beta}{C}\,\{f_L(x,\beta) - f_R(x,\beta)\} \\
& \times \Big\{ \mathrm{Im}\, c_d^\gamma \,\Big[(1 - P_e\, P_{\bar{e}})\,\Big(2\, c_v^\gamma \;+\; (r_L + r_R)\, c_v^Z\Big) \\
& +\; (P_{\bar{e}} - P_e)\,(r_L - r_R)\, c_v^Z\Big] \\
& + \mathrm{Im}\, c_d^Z \,\Big[(1 - P_e\, P_{\bar{e}})\,\Big((r_L + r_R)\, c_v^\gamma \;+\; (r_L^2 + r_R^2)\, c_v^Z\Big) \\
& +\; (P_{\bar{e}} - P_e)\,\Big((r_L - r_R)\, c_v^\gamma \;+\; (r_L^2 - r_R^2)\, c_v^Z\Big)\Big\}\,,
\end{aligned} \tag{10}$$

[5]Our expression for the up-down asymmetry agrees with that given in the errata of ref. [5].

where

$$
\begin{aligned}
C &= (1-P_e\,P_{\bar{e}})\,\Big\{(3-\beta^2)\,\Big[\Big(c_v^\gamma + r_L c_v^Z\Big)^2 \,+\, \Big(c_v^\gamma + r_R c_v^Z\Big)^2\Big] \\
&\quad +\, 2\beta^2 (c_a^Z)^2\,\Big(r_L^2 + r_R^2\Big)\Big\} \\
&\quad + (P_{\bar{e}} - P_e)\,\Big\{(3-\beta^2)\,\Big[\Big(c_v^\gamma + r_L c_v^Z\Big)^2 \,-\, \Big(c_v^\gamma + r_R c_v^Z\Big)^2\Big] \\
&\quad +\, 2\beta^2 (c_a^Z)^2\,\Big(r_L^2 - r_R^2\Big)\Big\}, \qquad (11)
\end{aligned}
$$

and the lepton energy distribution in t decay is given for left and right top helicities by [9]

$$
f_{L,R}(x,\beta) = \int_{\frac{x}{1+\beta}}^{\frac{x}{1-\beta}} f(x_0)\,\frac{\beta\,x_0 \mp (x-x_0)}{2\,x_0^2\,\beta^2}\,dx_0, \qquad (12)
$$

$f(x_0)$ being the distribution in the t rest frame,

$$
f(x_0) = \frac{x_0(1-x_0)}{\frac{1}{6} \,-\, \frac{1}{2}\left(\frac{m_W}{m_t}\right)^4 \,+\, \frac{1}{3}\left(\frac{m_W}{m_t}\right)^6}\;\theta(1-x_0)\,\theta(x_0 - \frac{m_W^2}{m_t^2}). \qquad (13)
$$

β is the top velocity in the cm frame, $\beta = (1-4m_t^2/s)^{\frac{1}{2}}$, and $-e r_{L,R}/s$ is the product of the Z-propagator and left-handed (right-handed) electron couplings to Z, with

$$
\begin{aligned}
r_L &= \frac{\left(\frac{1}{2} - x_w\right)}{\left(1 - \frac{m_Z^2}{s}\right)\,\sqrt{x_w\,(1-x_w)}}, \\
r_R &= \frac{-x_w}{\left(1 - \frac{m_Z^2}{s}\right)\,\sqrt{x_w\,(1-x_w)}}. \qquad (14)
\end{aligned}
$$

$$
\begin{aligned}
A_{ud} &= -\frac{3\pi\beta\sqrt{s}}{16 m_t C}\,\Big\{\mathrm{Re}\,c_d^\gamma\,\Big[(1-P_eP_{\bar{e}})(r_L - r_R)c_v^Z \\
&\quad +(P_{\bar{e}} - P_e)(2c_v^\gamma + (r_L + r_R)c_v^Z)\Big] \\
&\quad +\mathrm{Re}\,c_d^Z\,\Big[(1-P_eP_{\bar{e}})\,\Big((r_L - r_R)c_v^\gamma + (r_L^2 - r_R^2)c_v^Z\Big) \\
&\quad +\,(P_{\bar{e}} - P_e)\,\Big((r_L + r_R)c_v^\gamma + (r_L^2 + r_R^2)c_v^Z\Big)\Big]\Big\}, \qquad (15)
\end{aligned}
$$

$$
\begin{aligned}
A_{ud}^{fb} &= \frac{\beta^2\sqrt{s}}{4m_tC}c_a^Z\,\{\mathrm{Re}\,c_d^\gamma\,[(1-P_eP_{\bar e})(r_L+r_R) \\
&\quad +(P_{\bar e}-P_e)(r_L-r_R)] \\
&\quad +\mathrm{Re}\,c_d^Z\left[(1-P_eP_{\bar e})(r_L^2+r_R^2)+(P_{\bar e}-P_e)(r_L^2-r_R^2)\right]\Big\}\,, \qquad (16)\\
A_{lr} &= -\frac{3\pi\beta^2\sqrt{s}}{16m_tC}c_a^Z\,\{\mathrm{Im}\,c_d^\gamma\,[(1-P_eP_{\bar e})(r_L-r_R) \\
&\quad +(P_{\bar e}-P_e)(r_L+r_R)] \\
&\quad +\mathrm{Im}\,c_d^Z\left[(1-P_eP_{\bar e})(r_L^2-r_R^2)+(P_{\bar e}-P_e)(r_L^2+r_R^2)\right]\Big\}\,, \qquad (17)\\
A_{lr}^{fb} &= \frac{\beta\sqrt{s}}{4m_tC}\Big\{\mathrm{Im}\,c_d^\gamma\left[(1-P_eP_{\bar e})(2c_v^\gamma+(r_L+r_R)c_v^Z)\right. \\
&\quad \left.+(P_{\bar e}-P_e)(r_L-r_R)c_v^Z\right] \\
&\quad +\mathrm{Re}\,c_d^Z\left[(1-P_eP_{\bar e})\left((r_L+r_R)c_v^\gamma+(r_L^2+r_R^2)c_v^Z\right)\right. \\
&\quad \left.+\,(P_{\bar e}-P_e)\left((r_L-r_R)c_v^\gamma+(r_L^2-r_R^2)c_v^Z\right)\right]\Big\}\,. \qquad (18)
\end{aligned}
$$

Let us first look at the unpolarized case. Whereas a measurement of $A_E(x)$ would determine only one combination of $\mathrm{Im}\,c_d^\gamma$ and $\mathrm{Im}\,c_d^Z$, A_{lr} andA_{lr}^{fb} could be used to determine two independent combinations, as can be seen from (17) and (18) (putting $P_e = P_{\bar e} = 0$). These could give $\mathrm{Im}\,c_d^\gamma$ and $\mathrm{Im}\,c_d^Z$ independently. Similarly, measuring A_{ud}^{fb} in addition to A_{ud} would help determine $\mathrm{Re}\,c_d^\gamma$ and $\mathrm{Re}\,c_d^Z$ independently. Using a single asymmetry can only determine a combination of dipole couplings, and in the absence of extra theoretical input cannot say anything about individual dipole couplings.

However, if e^- and e^+ beams have longitudinal polarization, measuring the value of an asymmetry for two different polarizations gives us two different combinations of dipole couplings, allowing us to disentangle them. It is sufficient to measure for two different polarizations any one CPT-even asymmetry to deduce both $\mathrm{Re}\,c_d^\gamma$ and $\mathrm{Re}\,c_d^Z$, and any one CPT-odd asymmetry to deduce $\mathrm{Im}\,c_d^\gamma$ and $\mathrm{Im}\,c_d^Z$.

The two methods described above could have different sensitivities. Moreover, the sensitivity would be dependent on which asymmetries are chosen within each method, and we will later discuss our results in this context. The measure of sensitivity we use is the 90% confidence level (C.L.) limit on the dipole couplings which can be derived from a sample of appropriate events,

and is given by

$$\delta c_d^i = \frac{1.64\,\sqrt{N}\,c_d^i}{A}, \tag{19}$$

where A/c_d^i is the asymmetry for unit c_d^i (assuming the other $c_d^i = 0$). When limits on both c_d^γ and c_d^Z are obtained independently, the factor 1.64 above is replaced by 2.15, corresponding to a 90% C.L. limit for two degrees of freedom.

We also find that in some cases the sensitivity is greatly enhanced by isolating the polarization-dependent part of the distribution. Thus, if we take a polarization asymmetrized sample, corresponding to $|d\sigma(P_e, P_{\bar{e}}) - d\sigma(-P_e, -P_{\bar{e}})|$, and evaluate all asymmetries with respect to this new sample, we get a different set of asymmetries with different sensitivities.

We now come to our numerical results. We assume that the NLC will have $\sqrt{s} = 500$ GeV and it is possible to have an integrated luminosity of $\int\mathcal{L} = 10\,\mathrm{fb}^{-1}$. We take $m_t = 174$ GeV and $x_w = .23$. We look at only semi-leptonic events, viz., when either of t or $\bar{t}$ decays leptonically, while the other decays hadronically.

Fig. 1 shows bands in the $\mathrm{Re}\,c_d^\gamma - \mathrm{Re}\,c_d^Z$ space which correspond to 2.15 σ limit (90 % C.L. for two degrees of freedom) obtained from A_{ud} and A_{ud}^{fb}, without polarization ($P_e = 0$). While A_{ud} or A_{ud}^{fb} taken singly can limit one of $\mathrm{Re}\,c_d^\gamma$ or $\mathrm{Re}\,c_d^Z$ when the other is known, both the asymmetries put together can provide independent limits on $|\mathrm{Re}\,c_d^\gamma|$ and $|\mathrm{Re}\,c_d^\gamma|$, of the order of 5 and 1.5 respectively, for $P_e = 0$. Also shown in Fig. 1 are the bands from A_{ud} for e^- polarization $P_e = \pm 0.5$ (with $P_{\bar{e}} = 0$). The limits obtainable are improved by an order of magnitude.

Fig. 2 is in the $\mathrm{Im}\,c_d^\gamma - \mathrm{Im}\,c_d^Z$ space, and gives 2.15 σ limits obtained from A_{lr} and A_{lr}^{fb}. Again, for $P_e = 0$, only a simultaneous search for both these asymmetries can put independent limits on $|\mathrm{Im}\,c_d^\gamma|$ and $|\mathrm{Im}\,c_d^Z|$, of the order of 0.7 and 6, respectively. Limits on A_{lr} with $P_e = \pm 0.5$, also shown in Fig. 2, can improve these numbers by a factor of about $5 - 7$.

In Figs. 1 and 2, we do not show the combined up-down (left-right) and forward-backward asymmetries for non-zero polarization for clarity. However, the effect of polarization in those cases is similar.

Thus, by using polarization, one can obtain independent limits of the order of 0.2-0.25 on three of the four dipole coupling parameters. The remaining parameter, $\mathrm{Im}\,c_d^Z$ can be constrained to about 0.8.

Having considered independent limits, we now consider limits obtained on either the electric or the weak dipole moment, assuming the other dipole moment to be zero.

For the energy asymmetry, we have estimated limits obtainable by fitting the asymmetry in the range $x = 0.1 - 1.5$. The improvement in sensitivity is about a factor about 3 for $P_e = -0.5$ as compared to $P_e = 0$ for $|\mathrm{Im}\, c_d^Z|$, whereas measurement of $|\mathrm{Im}\, c_d^\gamma|$ is insensitive to polarization. However, on considering a polarization asymmetrized sample (as described above), the sensitivity for $|\mathrm{Im}\, c_d^Z|$ is improved by a factor of about 12 as compared to the unpolarized case, giving the best attainable 90% C.L. limit as 0.06.

The polarization asymmetrized distributions for $P_e = 0.5$ leads to an improvement in the sensitivities from the measurement of A_{ud} and A_{ud}^{fb}, whereas the sensitivity is worse in the case of A_{lr} and A_{lr}^{fb}. For example, A_{ud} can give a limit on $\mathrm{Re}\, c_d^\gamma$ of 0.04 as compared to 0.10 obtained without the asymmetrization procedure.

One can also consider combinations of the different procedures mentioned above to maximize the sensitivity available. We do not enter into these details in this short note, since our purpose is merely to point out the advantage that beam polarization can afford.

We end with the conclusions and a discussion of issues needing further study.

We have calculated several CP-violating asymmetries which can arise in the process $e^+ e^- \rightarrow t\bar{t}$, with subsequent $t, \bar{t}$ decay, in the presence of electric and weak dipole couplings of the top quark. In order to disentangle the CP-violating dipole couplings from each other, at least two T-odd asymmetries are needed for the real parts and two T-even asymmetries are needed for the imaginary parts, and we calculated possible asymmetries which could be used for the purpose. It was shown that longitudinal polarization of the electron can help in separating the various parameters, and in addition, leads to higher sensitivity. At the NLC with $\sqrt{s} = 500\, GeV$ and polarized electron beams with $\pm 50\%$ polarization, 90% C.L. sensitivities of the order of 0.25 are obtainable on independent determinations $|\mathrm{Re}\, c_d^\gamma|$, $|\mathrm{Re}\, c_d^Z|$, and $|\mathrm{Im}\, c_d^\gamma|$, respectively, and a sensitivitiy of about 0.8 for $|\mathrm{Im}\, c_d^Z|$.

Of these, the measurements of the real parts of $c_d^{\gamma,Z}$ are free from CP-invariant background contributions. As for the T-even asymmetries depending on the imaginary parts of $c_d^{\gamma,Z}$, the backgrounds from order-α collinear initial-state photon emission have to be calculated and subtracted. This will

be treated elsewhere. As mentioned earlier, the background can be reduced by imposing a cut on the visible energy.

The theoretical predictions for $c_d^{\gamma,Z}$ are at the level of $10^{-2} - 10^{-3}$, as for example, in the Higgs-exchange and supersymmetric models of CP violation. Hence the measurements suggested here cannot exclude these models at the 90% C.L. However, as simultaneous model-independent limits on both c_d^Z and c_d^γ, the ones obtainable from the experiments we suggest, are an improvement over those obtainable from measurements in unpolarized experiments.

Increase in polarization beyond ± 0.5 can substantially increase the asymmetries in some cases we consider. Also, the $e^+ e^-$ cm energy can also have an effect on the asymmetries. A discussion of these effects is relegated to a future publication.

We have compared our results with those of [7], where CP-odd momentum correlations are studied in the presence of e^- polarization. With comparable parameters, the sensitivities we obtain are comparable to those obtained in [7]. In some cases our sensitivities are slightly worse because we require either t or $\bar{t}$ to decay leptonically, leading to a reduced event rate. However, the better experimental efficiencies in lepton momentum measurement may compensate for this loss.

Inclusion of experimental detection efficiencies may change our results somewhat. However, the main thrust of our conclusions, that longitudinal beam polarization improves the sensitivity, would still be valid.

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Figure Captions

Fig. 1. Bands showing 90% C.L. on the $\mathrm{Re}\, c_d^\gamma$ and $\mathrm{Re}\, c_d^Z$ coming from A_{ud} (solid lines) and A_{ud}^{fb} (long-dashed lines) in the unpolarized case, and from A_{ud} with electron polarization $P_e = -0.5$ (short-dashed lines) and $P_e = +0.5$ (dotted lines).

Fig. 2. Bands showing 90% C.L. on the $\mathrm{Im}\, c_d^\gamma$ and $\mathrm{Im}\, c_d^Z$ coming from A_{lr} (solid lines) and A_{lr}^{fb} (long-dashed lines) in the unpolarized case, and from A_{lr} with electron polarization $P_e = -0.5$ (short-dashed lines) and $P_e = +0.5$ (dotted lines).

This figure "fig1-1.png" is available in "png" format from:

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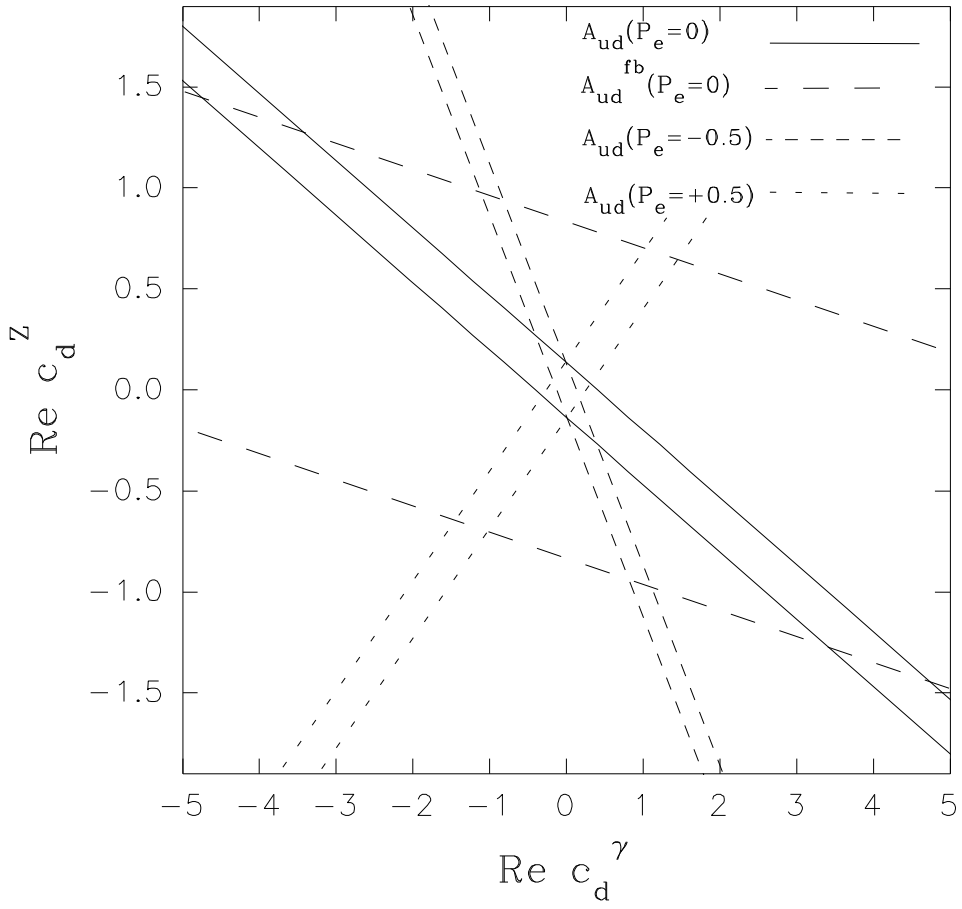
$A_{ud}(P_e=0)$
$A_{ud}^{fb}(P_e=0)$
$A_{ud}(P_e=-0.5)$
$A_{ud}(P_e=+0.5)$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−5
−4
−3
−2
−1
0
1
2
3
4
5
Re c_d^Z
Re c_d^γ

Fig. 1

This figure "fig1-2.png" is available in "png" format from:

http://arXiv.org/ps/hep-ph/9410357v1

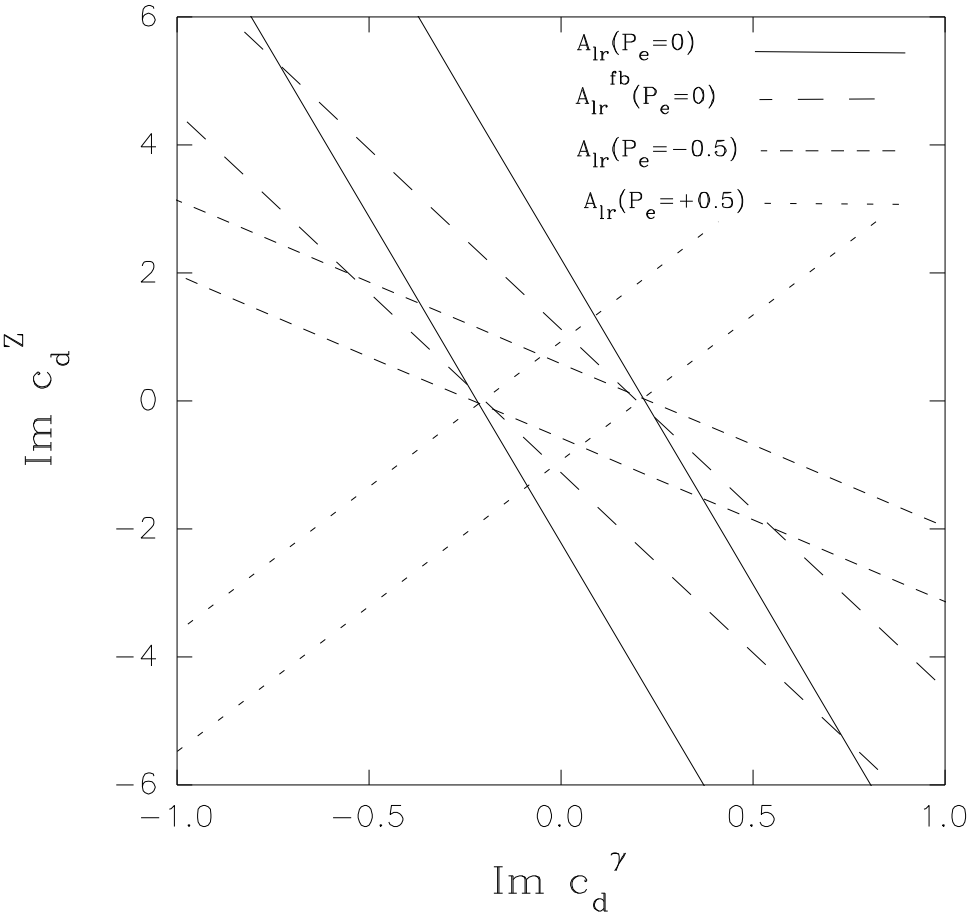
6
4
2
0
−2
−4
−6
−1.0
−0.5
0.0
0.5
1.0
Im c_d^z
Im c_d^γ
A_lr(P_e=0)
A_lr^fb(P_e=0)
A_lr(P_e=−0.5)
A_lr(P_e=+0.5)

Fig. 2